Progress Report — DOE/ARM grant #DE-FG03-00ER62929 — July 2000

Improved Water Vapor Measurements and Treatment of Ice-supersaturation in the Upper Troposphere from Vaisala RS80-H and RS90-H Radiosondes

Larry Miloshevich and Andrew Heymsfield (NCAR)
Ari Paukkunen (Vaisala)

Scientific Goals

Our research program aims to improve the accuracy of ARM radiosonde relative humidity (RH) measurements by developing an algorithm that corrects for the slow time-response of the sensors at cold temperatures, based on laboratory measurements of the sensor time-constant as a function of temperature. The second goal of our research program is to statistically characterize the magnitude of ice-supersaturation in supersaturated layers based on a dataset of humidity measurements from the NOAA/CMDL balloon-borne cryogenic hygrometer, then apply the results to the corrected radiosonde measurements. We will validate the correction algorithm using simultaneous measurements from Vaisala radiosondes and the NOAA hygrometer, then assess the impact of the corrections on the ARM dataset, and publish the results.

Accomplishments

Although the official start date for this research program is April 1, 2000 and funding was only received two months ago, considerable progress has been made on initiating the research. Obviously no substantial conclusions have been reached at this time, but the primary accomplishments are summarized as follows:

- Time-constant measurements are actively underway at Vaisala. In the meantime, we are using an approximation for the temperature-dependence of the time-constant based on previous measurements.
- The mathematical basis of the sensor response model has been derived from first principles, and a numerical implementation is evolving.
- The general framework of a time-lag correction algorithm has been developed, and initial results demonstrate "proof-of-concept" that a correction algorithm is possible. Initial results have shed light on the challenges posed by the 1% RH measurement resolution and the 2 s time resolution of the ARM data, as elaborated below.

Description of Progress

1. Mathematical Model of Sensor Response

The Vaisala humidity sensors respond to changes in the ambient humidity according to the common "growth-law" equation:

$$\frac{dU_m}{dt} = k \cdot (U_a - U_m), \tag{1}$$

where U_m is the measured humidity and U_a is the true ambient humidity at time t, and k is a constant. If U_a is constant during the time interval t_1 to t_2 (one timestep), then the solution of Eq. (1) gives the sensor response during the timestep:

$$U_m(t_2) = U_a(t_2) - [U_a(t_2) - U_m(t_1)] \cdot X, \tag{2}$$

where $X = e^{-(t_2-t_1)/\tau(T)}$, and $\tau(T) = 1/k$ is the temperature-dependent time-constant (63% response time).

The primary assumption in Eq. (2) is that the ambient humidity during each timestep is constant. A more realistic assumption is that the ambient humidity varies linearly during a timestep, in which case U_a in Eq. 1 is replaced by $U_a(t) = U_a(t_1) + A \cdot (t - t_1)$, where A is the slope of the ambient humidity profile. The (much more complicated) solution of Eq. (1) gives the sensor response to a linear ambient humidity profile:

$$U_m(t_2) = U_a(t_2) - A \cdot \tau \cdot (1 - X) - [U_a(t_1) - U_m(t_1)] \cdot X \tag{3}$$

Figure 1 shows the sensor response (curves 0,1,2) to a steep ambient humidity gradient (curve A), as calculated using the two different sensor response models. When U_a is approximated by step-changes (Eq. 2), with a timestep of either 2 s (curve 0) or 0.1 s (curve 1), it is clear that the step-change approach is not sufficiently accurate under all conditions for the 2-second time-resolution of the ARM data. However, the linear U_a profile is represented exactly in Eq. 3, and the resulting sensor response (curve 2) is equivalent to the step-change approach if the timestep goes to zero. There are advantages and disadvantages in the numerical implementation of both approaches; however, Eq. (3) is conceptually a superior model because a linear U_a profile between data points is more realistic and less sensitive to the time-resolution of the data than is the step-change approach of Eq. (2).

2. Preliminary Time-lag Corrections

A time-lag correction gives the ambient humidity profile that is consistent with the measured profile and one of the sensor response models given by Eq. (2) or Eq. (3). Rearranging Eq. (2) gives the constant ambient humidity $U_a(t_2)$ that would cause the measurement to change from $U_m(t_1)$ to $U_m(t_2)$ during the timestep:

$$U_a(t_2) = \frac{U_m(t_2) - U_m(t_1) \cdot X}{1 - X} \tag{4}$$

Similarly, rearranging Eq. (3) and substituting $A = [U_a(t_2) - U_a(t_1)]/(t_2 - t_1)$ gives the ambient humidity $U_a(t_2)$ assuming that it changed linearly from $U_a(t_1)$:

$$U_a(t_2) = \frac{[U_m(t_2) - U_m(t_1) \cdot X] + U_a(t_1) \cdot [X - \frac{\tau}{t_2 - t_1} \cdot (1 - X)]}{1 - \frac{\tau}{t_2 - t_1} \cdot (1 - X)} \tag{5}$$

Figure 2 shows part of an ARM RS80-H humidity profile (dashed curves) that has been corrected for time-lag error (solid curves), based on Eq. (4) and its assumption that U_a is constant between the 2-second data points. Panel A is a direct application of Eq. (4) to the original measurements, and illustrates the substantial impact of the 1% RH resolution of the measurements. Although the sensor itself responds in a continuous fashion, the data are truncated to 1% RH resolution, frequently leading to periods when the reported measurement is constant. A constant sensor response can only mean that U_a=U_m, because there is no "driving force" to produce change in the measurement. Furthermore, the minimum change in U_m of 1% RH can produce large spikes because 1% RH is quite a drastic change to occur during a 2 s time period if the temperature is cold and the time-constant is long. Acknowledging that the sensor response is really continuous, the data in Panel B are linearly interpolated across the constant periods before applying Eq. (4). The interpolated measurements are more realistic than the original truncated measurements, but spikes in U_a still occur when the slope of the U_m profile changes abruptly (and unrealistically). Smoothing either U_m or U_a with a 3-point average compensates for unrealistic changes in the slope of U_m (Panels C and D), but scrutiny of the results shows that simple linear interpolation and averaging is not the best approach because occasionally the modified measurements can differ from the original measurements by >1% RH, and overall consistency requires that any changes to the original measurements to compensate for truncation must be less than the measurement resolution. However, analysis has led to several ideas on compensating for the measurement resolution in a more realistic way. Investigating these ideas is one of the next steps in this investigation.

Figure 3 shows the same sounding that has been corrected for time-lag error based on Eq. (5), assuming that U_a changes linearly between the 2-second data points. Panel A shows the corrected profile after linear interpolation of the data across periods when U_m is constant. The fluctuations arise because, unlike the step-change approach, each corrected data point $U_a(t_2)$ depends on the previous corrected point $U_a(t_1)$, so continuous compensation by the correction is required to maintain consistency with unrealistic measurements. The fluctuations are reduced if the measurements are first smoothed by averaging (Panel B). If the measurements are not averaged but instead each corrected U_a value is averaged with the preceding point (Panel C), the trend within the fluctuations becomes apparent. Note that the modified measurements U_m that are consistent with the smoothed U_a profile can be derived from Eq. (3) and then checked against the original U_m measurements to ensure that the modified measurements do not differ by more than 1% RH. These preliminary investigations suggest that it may be more reasonable to smooth or adjust U_a and then iteratively check consistency of the corresponding U_m with the original measurements than it is to begin with smoothing of U_m. For example, averaging of U_a is a linear operation that is physically reasonable and consistent with the sensor response model of Eq. (5), whereas averaging of U_m is largely arbitrary and not consistent with the complicated form of the actual sensor response described by Eq. (3).

Publications

None currently. The plan is to write a paper on correcting Vaisala humidity data for time-lag error, including an assessment of the impact of the correction on the ARM dataset. This will likely occur in the latter half of this three-year research program. We also hope to write another paper that parameterizes the vertical distribution of ice-supersaturation in supersaturated layers, depending on the outcome of that analysis. Also, it is possible that collaborative efforts with other ARM researchers will arise.

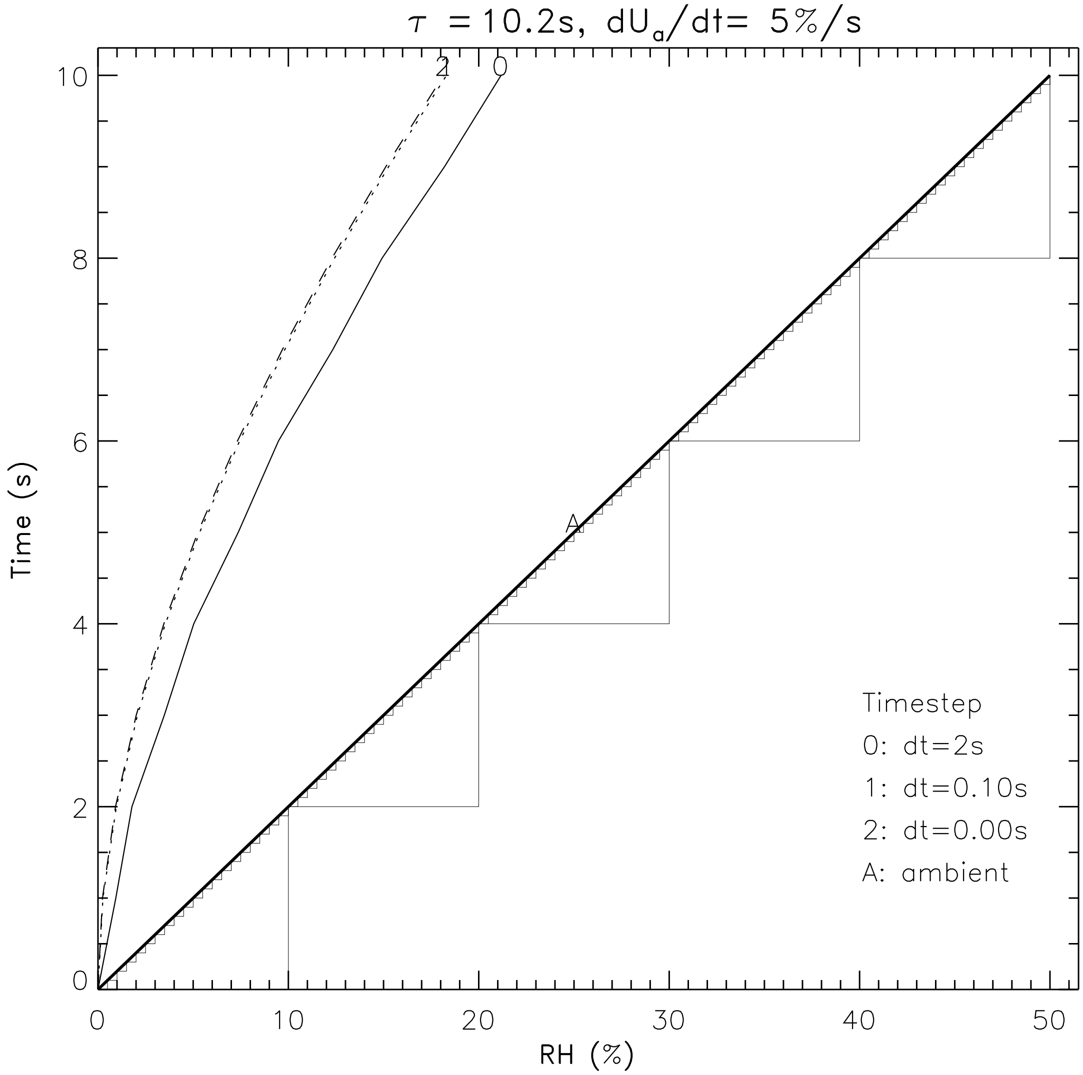

Figure 1: Two models for simulating the response of an RS80-H humidity sensor (curves 0,1,2) to a linear ambient humidity profile (curve A). Curves 0 and 1 assume the ambient humidity (U_a) is approximated by the indicated series of step-changes according to Eq. (2), for a timestep of either 2 s (like the ARM data) or 0.1 s. Curve 2 is based on the exact response equation for a continuous linear change in U_a (Eq. 3), which is equivalent to allowing the timestep of step-changes to approach zero. The simulated humidity gradient is somewhat steep to show the dependence on the choice of timestep and sensor response model, although this gradient does occur in real humidity profiles. The temperature for the simulations is -20°C, where the sensor time-constant is 10.2 s.

Simple Preliminary Implementations of a Humidity Time-lag Correction
Ua=constant during each timestep (i.e. step-changes; Eq. 4)

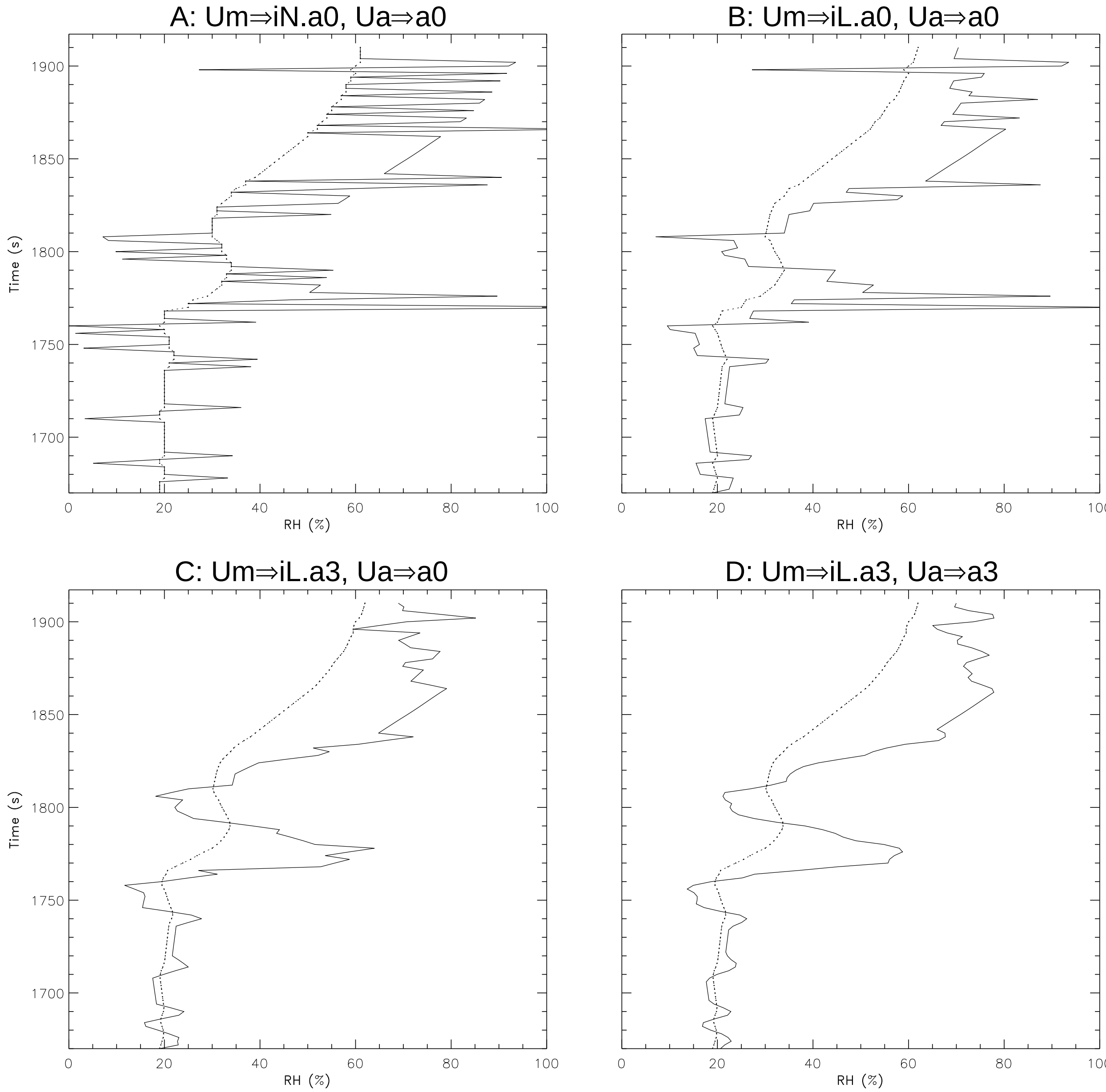

Figure 2: A portion of an ARM RS80-H humidity profile corrected for time-lag error based on Eq. (4), which assumes the ambient profile consists of step-changes with constant humidity between the 2-second data points. Each panel shows the impact of different data-smoothing operations. Dashed curves show the measurements after any smoothing is applied, and solid curves show the corresponding corrected (i.e. "ambient") humidity profile. The smoothing operations that were applied to either the measured profile (U_m) or the resulting ambient profile (U_a) are given by the codes in each figure title: "a3" indicates that a boxcar average of width 3 data points was applied, and "iL" indicates linear interpolation of the measurements across periods when U_m is constant as a result of the 1 %RH resolution of the data ("iN" indicates "No interpolation", where the actual measurements are used). For example, the correction in Panel D involved the following operations: 1) linearly interpolate across periods when U_m is constant, then smooth U_m with a 3-point average; 2) determine U_a from U_m using Eq. (4); and 3) smooth the resulting U_a with a 3-point average. The temperature of this data is about -40°C, and the sensor time-constant is about 45 s.

Simple Preliminary Implementations of a Humidity Time-lag Correction
Ua(t)=linear during each timestep (Eq. 5)

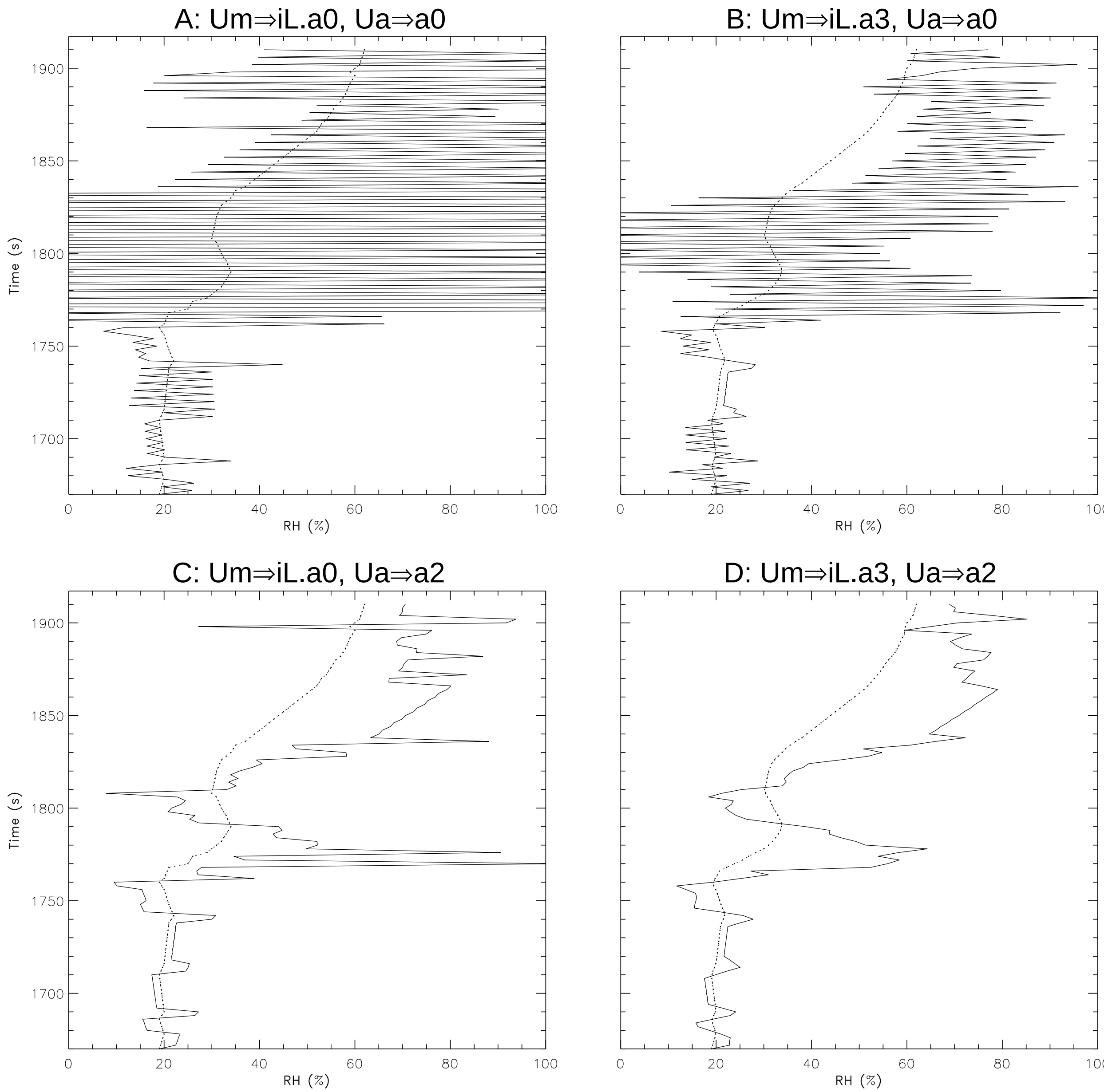

Figure 3: A portion of an ARM RS80-H humidity profile corrected for time-lag error based on Eq. (5), which assumes the ambient profile consists of continuous linear changes in humidity between the 2-second data points. Each panel shows the impact of different data-smoothing operations. Dashed curves show the measurements after any smoothing is applied, and the solid curves show the corresponding corrected (i.e. "ambient") humidity profile. The smoothing operations that were applied to either the measured profile (U_m) or the resulting ambient profile (U_a) are given by the codes in each figure title: "a3" indicates that a boxcar average of width 3 data points was applied, and "iL" indicates linear interpolation of the measurements across periods when U_m is constant as a result of the 1 %RH resolution of the data. For example, the correction in Panel D involved the following operations: 1) linearly interpolate across periods when U_m is constant, then smooth U_m with a 3-point average; 2) determine U_a from U_m using Eq. (5); and 3) smooth the resulting U_a with a 2-point average. The temperature of this data is about -40°C, and the sensor time-constant is about 45 s.